Distributed Load Control of Autonomous Renewable Energy Systems

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***Abstract*—Autonomous renewable energy systems such as wind, solar, and micro-hydro require control methods to maintain stability, due to the real time variation of input energy and load, while maximizing the use of renewable energy. This paper describes the application of load control using a novel frequency and voltage-sensing device. The device uses a low cost microcontroller to monitor the system frequency and voltage. Load switching is carried out based on this information.**

Software was developed for frequency and voltage measurements and tested on a 18 kW, single phase, 50 Hz, micro-hydro system. A fuzzy control system was then developed which makes intelligent load switching decisions using inputs from the measurement algorithms coupled with expert knowledge expressed in the form of control rules. This load control system was then tested on the same micro-hydro system and on a site powered by a 60 kW, 3 phase, 50 Hz wind turbine only.

***Index Terms*—Autonomous, frequency measurement, fuzzy control, load control, microcontroller, renewable energy.**

I. Introduction

AUTONOMOUS renewable energy systems such as wind, solar, and micro-hydro require control methods to maintain stability, due to the real time variation of input energy and load, while maximizing the use of the renewable resource. Unlike conventional engine driven autonomous power systems which use governors for frequency control, small autonomous renewable energy systems may be controlled using either load control or energy storage.

Storage devices such as batteries, flywheels, and hydraulic accumulators [1] have all been considered for frequency control but are often rather expensive and complex to control. Simple load control has been used in autonomous systems on Fair-Isle [2] and Lundy Island [3] in the UK and in a number of laboratory experiments, e.g., [4].

This paper describes an advanced distributed load control system using a low cost, microcontroller based, frequency and voltage-sensing device. Each load control device is based on a PIC16C711 microcontroller with no direct communication between them. Individual single-phase loads are connected to the supply through these devices. Distributed load control systems can be more robust than centralized systems because if one load controller fails the system can continue to function.

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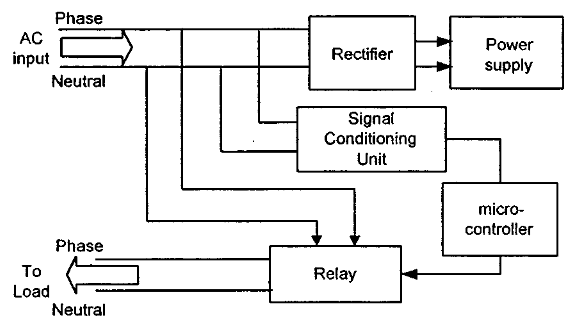

Fig. 1. Schematic diagram of frequency and voltage-sensing device.

The microcontrollers measure the frequency and voltage, and use this information to connect or disconnect the loads. Sections II and III of this paper describe the development and testing of the measurement techniques. Sections IV and V present the development of a fuzzy control algorithm for the load switching decision and the results of site tests on an autonomous micro-hydro and a wind only system.

II. Development and Testing of Frequency and Voltage Measurement Techniques

A. Frequency and Voltage Measurement Algorithms

Fig. 1 shows the schematic diagram of the frequency and voltage-sensing device.

A number of frequency measurement algorithms [5] were investigated including zero crossing detection, level crossing detection, superposition and Fast Fourier Transform based frequency measurement. The level crossing detection algorithm was preferred as it allowed multiple frequency estimates per cycle and multiple use of voltage samples.

1) Level Crossing Detection (LCD) Algorithm: The LCD algorithm [6] estimates the frequency deviation of the signal from the nominal frequency. The input voltage signal is sampled at a constant rate, n samples per cycle, at a sampling time of τ ms, such that $n\tau$ is close to the time period of the nominal frequency. The samples in the previous cycle are projected to the next cycle of the voltage signal. This projected distance equals the time period T of the signal, which is unknown. Since $n\tau$ is fixed, calculating the deviation x from $n\tau$ enables the time period of the signal to be calculated as shown in (1)

$$T = n\tau - x. \tag{1}$$

The deviation at any time t, $x(t)$, is calculated from four voltage samples by applying linear interpolation as shown in (2)

$$x(t) = \frac{(V(t) - V(t - n\tau))}{2} \times \left[\frac{1}{(V(t) - V(t - \tau))} + \frac{1}{(V(t - n\tau + \tau) - V(t - n\tau))}\right] \times \tau \qquad (2)$$

where $V(t)$ and $V(t-\tau)$ are the present and previous samples in the current cycle. $V(t-n\tau)$ and $V(t-n\tau+\tau)$ are the samples in the previous cycle separated by a distance of $n\tau$ and $(n-1)\tau$ from the present sample.

Thus, an estimation of the time period and hence the frequency is possible at each sampling instant. However, a weighted mean of several (m) estimates of $x(t)$, as shown in (3), is used to obtain the frequency estimate.

$$X(m, t) = \frac{\sum_{k=1}^{m} [x_k(t) \times w_k(t)]}{\sum_{k=1}^{m} [w_k(t)]} \times \tau \qquad (3)$$

where $x_k(t)$ is $x(t)$ at sample k and$w_k(t)$ is the weighting factor $w(t)$ at sample k. The weighting factor calculation can be found in [6].

2) RMS Voltage Measurement: Fixed and moving window configurations were investigated for the rms voltage measurement. In a fixed window configuration of N samples width, the voltage estimates were obtained every N samples as shown by (4).

$$V_{\rm rms}^2 = \frac{\sum_{n=1}^{N} V_n^2}{N} \qquad (4)$$

where, $V_1, V_2 \cdots V_n$ are the instantaneous voltage samples.

In the moving window configuration, the voltage estimates were obtained at every sampling instant as shown by (5).

$$V_{{\rm rms},\, i}^2 = \frac{\sum_{n=(i-N)}^{i-1} V_n^2 + V_i^2 - V_{i-N}^2}{N}. \qquad (5)$$

A switching-decision count, K, of consecutive estimates which must exceed the threshold setting before a switching decision is taken was used to ensure correct operation of the load controllers. This was applied to both the frequency and fixed window voltage measurements.

B. PSCAD/EMTDC Simulation of Measurement Techniques

A model was developed, to calculate frequency and voltage using the level crossing detection and rms voltage measurement algorithms, in the electromagnetic transient program, PSCAD/EMTDC [7].

The model used $n = 10$, $m = 12$, and $\tau = 2.295$ ms, and provided frequency estimates every 12 samples. An error of 0.19 Hz was noted at 51 Hz in a test frequency range between 44 Hz and 51 Hz. It was found that the LCD algorithm required 50 ms to detect a frequency variation.

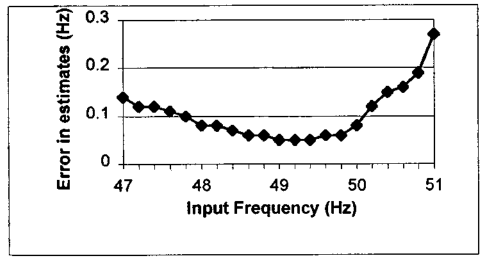

Fig. 2. ICE test result—Error variation of the LCD algorithm.

The error in the rms voltage estimates, for a 230 V signal, was ±1.05 V for a fixed window configuration of 13 samples width. For a voltage variation, the minimum response time was found to be 47 ms. For the moving window configuration of same window width, the error was only ±0.8 V and the response time was 40 ms.

These simulation results showed that the LCD algorithm and the moving window configuration algorithm were able to give fast and accurate frequency and voltage estimates, respectively.

C. Laboratory Testing of the Measurement Techniques

Assembly language code [5] for the measurement techniques was developed. The parameters used in the code were the same as that of the EMTDC simulation. The code was programmed into the microcontroller and tested in real time using an In-Circuit Emulator (ICE), and a relay test set.

1) ICE Test:

a) Performance of the Frequency Measurement Algorithm: The detailed description of the test set up and the procedure can be found in [5]. Fig. 2 shows the variation of the error in the estimate of different input frequencies.

It can be seen that the error is less than 0.1 Hz for frequencies between 48 Hz and 50 Hz. The error has increased for other frequencies due to the limited resolution (8-bit) of the A/D converter. Therefore, to obtain accurate estimates for frequencies between 44 Hz and 46 Hz, 46 Hz and 48 Hz the sampling times were changed to 2.502 ms and 2.383 ms respectively. These sampling times were obtained from the PSCAD/EMTDC simulation by trial and error. Tests were carried out on the ICE for these frequency ranges using the modified sampling times and an error variation of 0–0.1 Hz was confirmed.

b) Performance of the Voltage Measurement Algorithm: Only the fixed window configuration was tested using the ICE. For a voltage signal of magnitude 230 V, an error of ± 3 V was found in the voltage estimates.

2) Use of Relay Test Set:

c) Testing of Frequency Measurement Algorithm: Fig. 3 shows the frequency variation obtained from a PC based relay test set (OMICRON) [8], and the microcontroller output. The response time (t_r) was measured to be 62.5 ms. This compared with the minimum response time of 50 ms obtained with the PSCAD/EMTDC simulation.

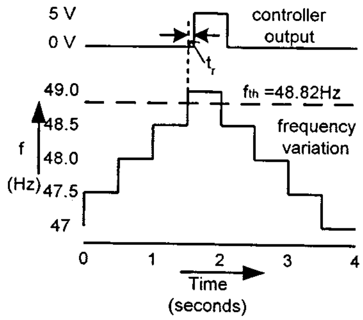

Fig. 3. Relay test set result—frequency measurement algorithm.

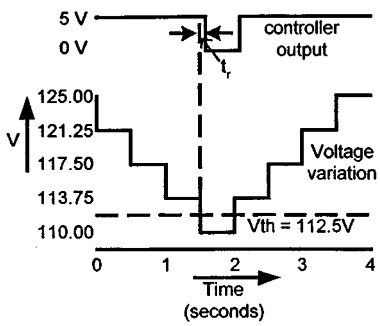

Fig. 4. Relay test set result—moving window voltage measurement algorithm.

d) Testing of Voltage Measurement Algorithms: Fig. 4 shows the voltage variation obtained from the relay test set, and the microcontroller output for the moving window voltage measurement algorithm.

From Fig. 4, the response time (t_r) was measured to be 45 ms compared to the 40 ms response time obtained from PSCAD/EMTDC simulation. This result shows good agreement between the simulation and laboratory tests. The slight difference in response times was due to the use of a simple first order infinite impulse response (IIR) type digital filter with a time constant of 4.6 ms in this test.

For a fixed window configuration, the response time was measured to be 62 ms. This result was also found to be in good comparison with the PSCAD/EMTDC simulation. Overall, the laboratory tests validated the PSCAD/EMTDC simulation results.

III. Site Test of Measurement Techniques

The test site was a micro-hydro power system, rated at 18 kW, single phase, 230 V, at Polmood in the UK. This system was chosen because it permitted flexible operation, including variation of the frequency and voltage. In addition, an existing electronic dump load controller heavily distorted the voltage waveform (Fig. 5).

A. Steady State Accuracy Test

1) Frequency Measurement Technique: For the site test, microcontrollers were programmed with various values of m and K. The use of larger values of m and K for the site tests increased the steady state accuracy but reduced the speed of response. A maximum measured error of 0.04 Hz was found even in the presence of the heavily distorted waveform.

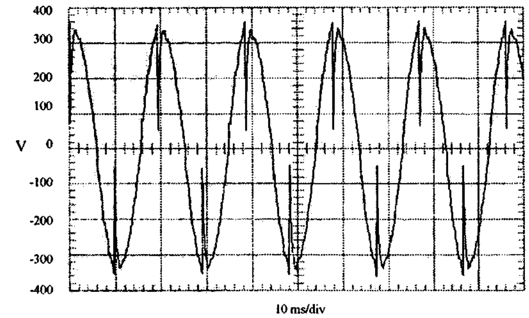

Fig. 5. Voltage waveform distortion by existing dump load controller.

2) Voltage Measurement Techniques: The moving and fixed window configurations were tested simultaneously. The moving window configuration used the digital filter with a time constant of 11.5 ms and the fixed window configuration used a switching-decision count (K) of 3. An error of 4 V was found for the moving window configuration and of 2 V for the fixed window configuration. The increase in error for the moving window configuration was due to the heavily distorted voltage waveform.

B. Transient Response Tests

1) Frequency Measurement Technique: The frequency measurement algorithm was tested for various threshold settings with a range of values of m and K from 10–15 and 3–5 respectively. An average response time of 175 ms was obtained from these tests with a fastest measured response time of 87 ms.

2) Voltage Measurement Techniques: Average response times of 58 ms and 88 ms were found for the moving and fixed window configurations respectively.

In summary, the site test confirmed that the LCD algorithm could be used for frequency measurement with an accuracy of 0.04 Hz and a response time of 175 ms even for the distorted waveform. For rms voltage measurement, the moving window configuration is preferred as it gave a faster response with a smaller error than the fixed window configuration. Optimization of the trade-off between accuracy and speed of response is the subject of continuing research.

IV. Development and Testing of Fuzzy Control System

A. Fuzzy Load Control Algorithm

The previous generation of load controllers [1]–[4] use a threshold system based on the generator droop characteristic to make the switching decisions. This system has two main disadvantages. Firstly some loads experience a much better service than others. Secondly the load controllers have to be configured for each system using a difficult process which involves finding suitable sizes of loads and setting the thresholds at the correct points on the droop characteristic.

To overcome these problems a fuzzy control system was developed to provide an improved frequency control solution. All the fuzzy controllers share a single target frequency and therefore do not require a complex set up procedure.

Fuzzy logic is particularly appropriate for systems where the sources of information are interpreted qualitatively, inexactly or

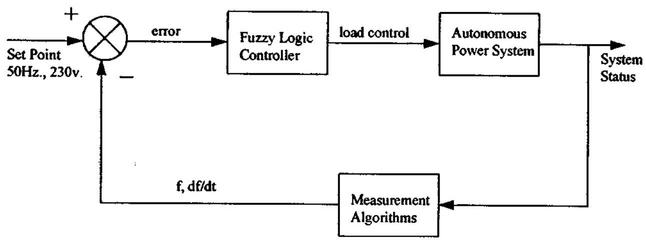

Fig. 6. Fuzzy control diagram.

TABLE I
FUZZY CONTROLLER DESIGN

Stage	Operator Selected
AND method	MIN
Implication	MIN
Aggregation	MAX
De-fuzzification	COM

uncertainly [9]. The control problem in question exhibits each of these features. For example, interpretation of system status is qualitative, any measurement algorithms are inexact and the generation and load profiles are uncertain.

The load controllers are required to operate on many autonomous systems with different power ratings, inertia constants, renewable energy sources and load profiles. Fuzzy control is robust and non linear and therefore is able to function well across this wide operating range.

Fuzzy controllers use verbal rules rather than mathematical relationships. This process is not computationally intensive [10] which results in fast execution times. This feature means they are attractive for real time control problems. Fig. 6. illustrates the control system being described.

The fuzzy control system was developed using the PIC fuzzyTECH software development system [11]. This package allows fuzzy code to be embedded directly into the microcontrollers.

The application is a multiple input single output, MISO system and uses state evaluation control rules. The process state is evaluated and a fuzzy control action is computed at time t as a function of the inputs and the control rules. The rules are of the form IF (process state1) AND (process state2) THEN (control output)

Measurement algorithms provide inputs of frequency and rate of change of frequency to the fuzzy controller. When designing a fuzzy controller there are many design choices, Table I. lists the fundamental fuzzy controller design choices made in this case.

The design choices made on the whole were conventional and can be found in [10], apart from the method of de-fuzzification which is less well known. The center of maximum method, COM, was chosen as it is an approximation of the more common and computationally intensive center of gravity method. The COM de-fuzzification method computed a crisp output and gave the best compromise between the inputs received.

Various rule bases and membership functions were tested using simulation software before selection of the final system

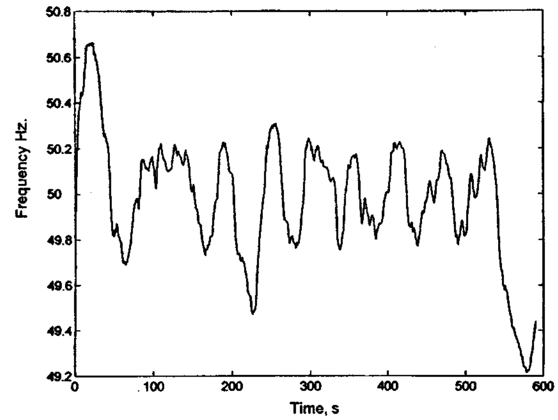

Fig. 7. MATLAB/SIMULINK simulation frequency control results.

was made. The rule base was designed using knowledge of power system dynamics and contained 9 rules. A trade off between system complexity and a simple low memory solution was required so that the final controller software could be stored in the limited program memory of the microcontroller.

The fuzzy controller produced a crisp value which advised one of the following output actions, Load on, Load off, or No action. The fuzzy controller also indicated the degree of truth in the control action advised. There is no overall supervisory controller for the load controllers and they did not communicate with each other. Therefore in order to ensure that the load controllers operate individually and that the energy is shared equitably among the loads, C code was developed to provide a random element to the load controllers. The code also ensured that the overall load connected was proportional to the degree of truth indicated by the fuzzy controller.

B. MATLAB/SIMULINK Simulation of Fuzzy Controllers

A computer model of a wind only system controlled by the fuzzy load controllers was developed using MATLAB/SIMULINK and was used to test the fuzzy controllers. The model included aerodynamic and electrical representations. The model used real wind speed data as an input and included over 100 load controllers switching varying sizes of load. The model allowed the fuzzy algorithm and the random load distribution software to be refined. It can be seen in Fig. 7. that the frequency was well controlled with maximum and minimum values of 50.7 and 49.2 Hz., respectively.

C. Laboratory Testing

The load controller hardware was modified to include a TRIAC rather than an electromagnetic relay. TRIACs have a longer lifetime than the electromagnetic relays and can switch at the higher frequencies required for effective power system control. The power rating was also increased so that the load controllers could switch loads of up to 7 kW.

A set of fifteen modified load controllers was built and incorporated into a single test unit. Before site testing the load controller hardware and software was thoroughly tested on a laboratory test rig comprising a 3 kW synchronous generator driven by a variable speed drive. The power generated was switched

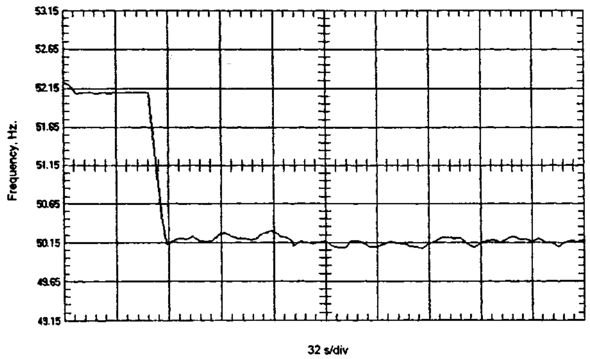

Fig. 8. Fuzzy control site test, micro-hydro turbine results.

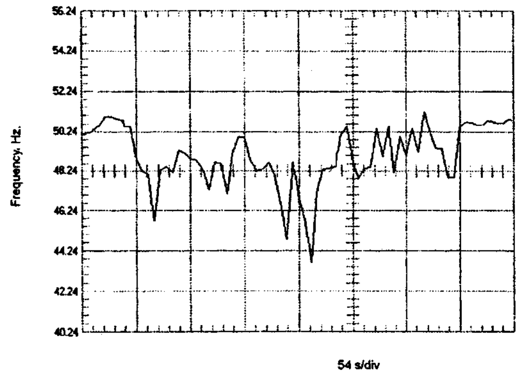

Fig. 9. Fuzzy control site test, wind turbine results.

through a bank of resistors using the fuzzy load controllers to govern the system frequency.

V. Site Tests

A. Micro-Hydro Site Test

The fuzzy load controllers were tested on the micro-hydro site described in Section III. The system was configured to generate around 14 kW. Fifteen, 1 kW loads were connected to the fuzzy load controllers and switched to maintain a stable frequency. It can be seen from Fig. 8 that the results were encouraging with frequency control of ± 0.2 Hz achieved. The existing dump load controller was controlling the system at 52 Hz during the initial period after that the system was under the sole influence of the fuzzy load controllers.

B. Wind Only Site Test

Site tests were performed on an autonomous wind only system with a nominal 60 kW, stall regulated, horizontal axis turbine, fitted with a 100 kVA synchronous generator. The load controllers were connected to 15 individual 6 kW loads. This allowed the turbine to be controlled solely by the fuzzy load controllers even at the peak power of 90 kW. Data-logging equipment was connected to record the system status whilst under fuzzy load control.

C. Test Results

The wind speed during the testing was low and varied from 3 m/s to 8 m/s. The turbine begins to generate appreciable power at around 6 m/s and reaches rated power at 13 m/s. Therefore during testing the wind power occasionally dropped to zero. The load controllers responded to the varying input power by switching the loads in an attempt to control the system frequency. Fig. 9. shows the system frequency when under the control of the fuzzy load controllers.

Fig. 9. shows that the frequency control, during a seven minute period, on the whole was between 51 and 48 Hz. with occasional dips due to lulls in wind speed. During these dips all the load controllers shed their loads and so these dips were unavoidable on a wind only system.

The results show that on the whole the system frequency is controlled to within the limits detailed in the EN50160 European standard document regarding voltage characteristics

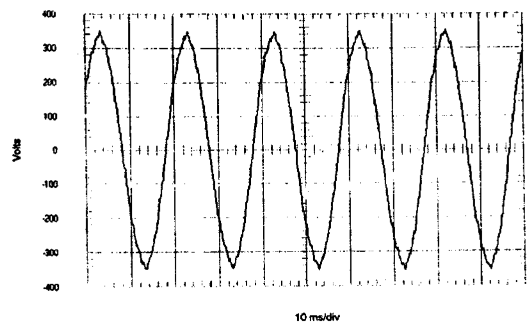

Fig. 10. Site test, voltage waveform with fuzzy zero crossing switching.

of autonomous systems [12]. The site results did not achieve the same level of frequency control as that produced by the MATLAB/SIMULINK model. This is because only 15 loads were used as opposed to 100 and the loads were relatively large. This causes the control to be coarse as the minimum control action is 6 kW. The frequency control was not as successful as for the micro-hydro system, as the input wind power is subject to greater fluctuations.

Zero crossing optical drivers were used to control the TRIACs to ensure that switching actions were taken at voltage zero crossings. This compromises the speed of response of the control system but minimizes the distortion of the voltage waveform. It can be seen in Fig. 10. that the distortion of the waveform is negligible in comparison to that caused by the dump load controller present at the micro-hydro site (Fig. 5).

VI. Conclusion

A new frequency and voltage-sensing device was applied for distributed load control of autonomous renewable energy systems. The performance of the measurement techniques was tested in the laboratory and on site. The tests showed that the measurement algorithms are able to provide accurate and fast frequency and voltage estimates even with a distorted waveform.

Fuzzy controllers were developed to control the system frequency adequately without any appreciable distortion of the voltage waveform. The fuzzy controllers offer a robust, low cost control solution applicable to a wide range of autonomous systems with a reduced need for customization.

Tests on other power systems are planned for the near future in particular a site with a wind turbine driven induction generator and synchronous compensator.

An element of on-line self-tuning of the fuzzy algorithms is also being considered.

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